

## GNSS and DGNSS Spoofing Detection

*Evgeny Ochinnikov*

Maritime University of Szczecin, Szczecin, Poland

E.Ochinnikov@AM.Szczecin.pl

**Abstract.** One of the main problems of modern navigation both manned and unmanned transport systems is a problem of transport safety. To improve the accuracy of transport positioning used Differential GNSS technology, which is based on setting a fixed referent station with a known position XYZ. Unfortunately, GNSS is vulnerable to malicious intrusion with the help of cyber-attacks as Jamming and Spoofing. GNSS signals and/or correction signals of DGNSS referent station can be jammed and/or spoofed by false signals, but special receivers can provide defenses against such attacks. How can the rover receiver (i.e., the user) be sure that the information they receive is authentic? Spoofing is the transmission of matched-GNSS-signal-structure and/or signals of referent station interference in an attempt to commandeer the tracking loops of a victim receiver and thereby manipulate the receiver's timing or navigation solution. A spoofer can transmit its counterfeit signals from a stand-off distance of several hundred meters, or it can be co-located with its victim. In this article we consider the principles of spoofing detection using mainly Differential GNSS, in which a correction signals of referent station uses for detection of spoofing.

**Keywords.** GNSS, DGNSS, differential station, reference station, radio beacon, antiterrorism, antispoofing.

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### 1. Introduction

Marine environments present some of the most challenging positioning conditions in the world — raging currents, rugged coastlines, narrow passageways and high winds. Modern satellite navigation is based on the use of no-request range measurements between navigational satellite and the user. It means that the information about the satellite's coordinates given to the user, is included into navigation signal. The way of range measurements is based on the calculation of the receiving signal time delay compared with the signals, generated by the users equipment [1].

Satellite based positioning provides the world's most precise location information. It is possible to acquire positioning anywhere in the world that GNSS satellite signals are available, any time of day, at data rates up to 100 Hz. Measurements can be generated in real time or processed post-mission to achieve the highest level of accuracy.

GNSS technology is most frequently used to:

- determine the location of an object on or with respect to the Earth for navigation;
- locate an object with respect to another object for tracking purposes.

Positioning information typically provided includes a horizontal domain (latitude/longitude or easting/northing) and a vertical domain (height).

To improve the accuracy of transport positioning used Differential GNSS technology, which is based on setting a fixed referent station with a known position XYZ. For example, Oceanix<sup>1</sup> provides accurate GNSS corrections to enable sub-decimetre positioning for marine hydrographic survey, dredging, mapping, coastal patrolling and other non-oil and gas marine applications. The high rate corrections broadcast enables carrier phase ambiguity resolution within the GNSS receiver, greatly enhancing the accuracy and speeding recovery from GNSS signal interruptions.

Oceanix Nearshore correction service delivers exceptional sub-decimetre positioning for diverse marine applications including dredging, hydrographic survey and mapping. The high-rate corrections broadcast enables carrier phase ambiguity resolution within the GNSS receiver, greatly enhancing the accuracy and speeding recovery from GNSS signal interruptions. Oceanix includes precise GNSS clock and orbit correction data providing high accuracy: 4 cm horizontal and 6 cm vertical.

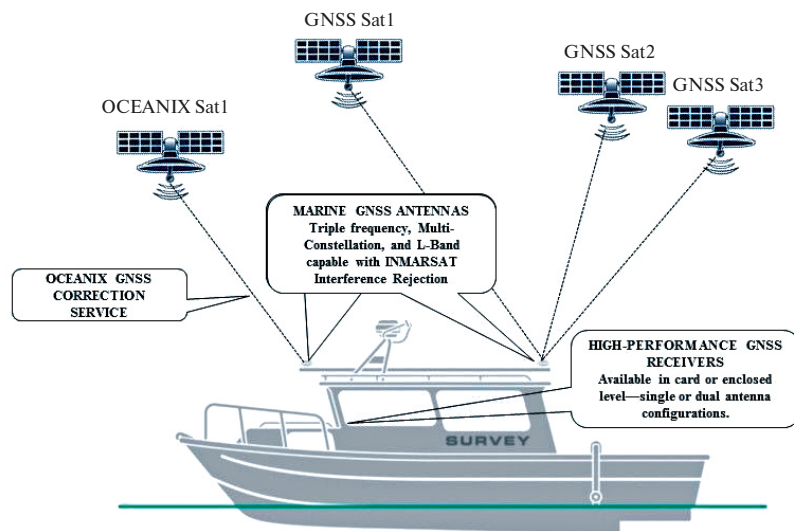


Fig. 1. OCEANIX GNSS correction service<sup>2</sup>

<sup>1</sup> Marine Brochure [Electronic recourse]. URL: <http://www.novatel.com/assets/Documents/Papers/Novatel-Marine-Brochure.pdf> [URL Address is available 5/14/2017 6:30 PM].

<sup>2</sup> Ibid.

Sometimes you do not need to know your precise position but you do need to know your position or an object's position, relative to another object or location. GNSS relative positioning solutions<sup>3</sup> are used to:

- determine where an object is located on earth with respect to another object's location;
- determine the horizontal and vertical distances between one object to another object (the horizontal and vertical distances can also be referred to as baseline lengths, displacements, relative separations or offsets between the two objects).

Applications requiring relative GNSS positioning include:

- landing systems such as helicopter to aircraft carrier;
- railway collision avoidance systems;
- autonomous in air refueling;
- safety systems where a device beep increases in volume as you approach another object or location;
- automated ship docking systems.

Main definitions:

- *GNSS* — Global Navigation Satellite System (GLONASS: [www.glonass-iac.ru](http://www.glonass-iac.ru), GPS: [www.navcen.uscg.gov](http://www.navcen.uscg.gov), BEIDOU: [en.beidou.gov.cn](http://en.beidou.gov.cn), GALILEO: [www.gsc-europa.eu](http://www.gsc-europa.eu), QZSS: [www.qzs.jp/en/services](http://www.qzs.jp/en/services)).
- *DGNSS* — Differential GNSS.
- $\text{Sat}_i, i = \overline{1, N}, N \geq 4$  — the navigation satellites as the space part of GNSS. {In ideal case, when the measurements are precise and satellite time is identical with the user's equipment time the users positioning can be realized with 3 satellites. Actually satellites time differs from the time on the users equipment. So, for users positioning one more coordinate is necessary — time drift between users equipment and the satellite time. That's why four satellites are needed for the solving of navigation problem.}
- *Almanac* is a package of ephemeris of all the satellites belong to global navigation system.
- *Ephemeris* — a coordinates package, which uniquely determine the satellites position and velocity.
- *DS* — *Differential Station* — control correction station subsystem differential GNSS, including a *Reference Station* with their own coordinates  $(x_{rs}, y_{rs}, z_{rs})$  and the *Radio Beacon* transmitting correction information.
- *Spoofing* — attack on GNSS, which is trying to deceive the GNSS receiver, transmitting the powerful false signals that mimic the signals from GNSS and exceeding the power of true signals from GNSS.

<sup>3</sup> GNSS Relative Positioning [Electronic recourse]. URL: <http://www.novatel.com/solutions/relative-positioning> [URL Address is available 5/14/2017 6:30 PM].

- *Spoofers* — complex computer and radio equipment for the implementation of GNSS spoofing.
- *Rover* — any mobile GNSS receiver that is used to collect data in the field at an unknown location.
- *Pseudo-range* — distance to the satellite, resulting in the receiver based on the correlation of the received code and on-board code without correction of clock synchronization errors.
- *RTCM* — *Radio Technical Commission for Maritime Services* — define a differential data link for the real-time differential correction of roving GNSS receivers.
- *WGS-84* — *World Geodetic System 1984* describes the shape of the Earth.
- $(x, y, z)$  — the real coordinates of the vehicle<sup>4</sup>.
- $(x_v, y_v, z_v)$  — the calculated coordinates of the vehicle using the GNSS.
- $(\tilde{x}_v, \tilde{y}_v, \tilde{z}_v)$  — the calculated coordinates of the vehicle using the DGNSS.
- $(x_{rs}, y_{rs}, z_{rs})$  — the coordinates of RS.
- We also denote for  $i = \overline{1, N}, N \geq 4$  :  
 $(x_i, y_i, z_i)$  — the coordinates of  $\text{Sat}_i$ ;  
 $T_i^{rs}$  — the propagation time from the  $\text{Sat}_i$  to the RS in vacuum;  
 $\hat{T}_i^{rs}$  — the propagation time from the  $\text{Sat}_i$  to the RS in real atmosphere;  
 $D_i^{rs}$  — the real distance from the  $\text{Sat}_i$  to the RS;  
 $\hat{D}_i^{rs}$  — the measurement result of the distance from the  $\text{Sat}_i$  to the RS (evaluations of  $D_i^{rs}$  or pseudo-range);  
 $\Delta D$  — the positioning error;  
 $T_i^v$  — the propagation time from the  $\text{Sat}_i$  to the vehicle in vacuum;  
 $\hat{T}_i^v$  — the propagation time from the  $\text{Sat}_i$  to the vehicle in real atmosphere;  
 $\hat{D}_i^v$  — the measurement result of the distance from the  $\text{Sat}_i$  to the vehicle (the vehicle pseudo-ranges).

## 2. GNSS and DGNSS Positioning

The distance from vehicle (Fig. 2) to satellites  $\text{Sat}_i$  can be written as

$$D_i^v = \sqrt{(x_i - x_v)^2 + (y_i - y_v)^2 + (z_i - z_v)^2} = c T_i^v, i = \overline{1, N}, N \geq 4. \quad (1)$$

<sup>4</sup>If the vehicle is 2D vehicle (ship, vessel, boat, car, etc.), the height coordinate ( $z$ ) can be omitted and minimum number of navigation satellites can be reduced to three ( $i = \overline{1, N}, N \geq 3$ ).

Since the measurement of distance from the vehicle to the satellites is carried out by measuring the propagation time  $\hat{T}_i^v = T_i^v + \Delta T_i^v$  of GNSS signals from  $\text{Sat}_i$  to vehicle then (1) can be represented as (excluding time synchronization errors):

$$\sqrt{(x_i - x_v)^2 + (y_i - y_v)^2 + (z_i - z_v)^2} = c\hat{T}_i^v, \quad i = \overline{1, N}, N \geq 4. \quad (2)$$

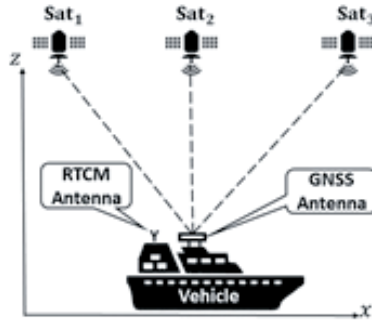


Fig. 2. GNSS:  $\text{Sat}_i$  — “Satellites”,  $i = \overline{1, N}, N \geq 4$ , the visible part of GNSS satellite constellation

The navigation processor of vehicle solves the system of the equations (2), calculate the position of the vehicle  $(x_v, y_v, z_v)$  and timing errors on board  $\Delta t$ , which are used to correct the clock GNSS navigation (this article is not consider the timing errors  $\Delta t$ )<sup>5</sup>. The positioning error may be defined as

$$\Delta D = \sqrt{(x - x_v)^2 + (y - y_v)^2 + (z - z_v)^2} \quad (3)$$

on condition that the real coordinates of the vehicle  $(x, y, z)$  known since the geodesic (centimeter) accuracy. Analyzing the problem of positioning accuracy (2), we note that

$$\left\{ \hat{T}_i^v = T_i^v + \Delta T_i^v \right\}, \quad i = \overline{1, N}, N \geq 4 \quad (4)$$

that is, the accuracy is largely determined by the size of the propagation time delay from the  $\text{Sat}_i$  to the vehicle  $\Delta T_i^v$ .

Support for GNSS Positioning technology will solve the problem of positioning in the meter range (5–10 m). Currently, to improve the accuracy of GNSS are widely used the differential GNSS.

<sup>5</sup> The calculations require the exact time, and most GNSS receivers do not contain sufficiently precise internal clock, therefore, to remove the ambiguity with respect to time, need another equation that allows to obtain the exact time — this equation gives a fourth satellite. Thus, for high-precision positioning receiver enough signals of four satellites.

### ➤ 2.1. Differential GNSS Positioning

In order to increase the accuracy of GNSS to a level that provides swimming ships in rivers and canals, was developed differential subsystem DGNSS [2–7], consisting of ground differential base stations that receive signals from satellites, counting errors for signals about its (actual) position in the system WGS84 and transmit errors by a special radio network or by satellite. Correcting Reed-Solomon codes are used for error-correcting coding. DGNSS are divided into three categories (Fig. 3).

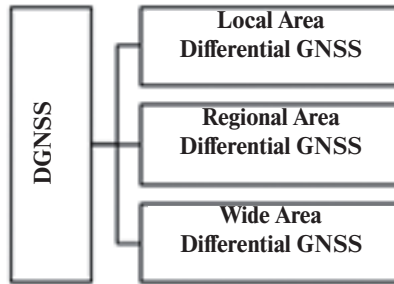


Fig. 3. LADGNSS — Local Area Differential; RADGNSS — Regional Area Differential GNSS; WADGNSS — Wide Area Differential GNSS

LADGNSS — Differential station transmitting correction information up to  $\sim 200$  km of coastline. RADGNSS — formed by combining data of a few LADGNSS that located in the same region. Master station transmitting correction information up to  $\sim M \cdot 200$  km of coastline, where  $M$  is number of LADGNSS. WADGNSS — formed by combining data of a few RADGNSS that located in a same region, a same state or a group of bordering states. The transmitting of correction information in the unlimited field of the Earth can be implemented in two ways: through a communication satellite or a group of satellites, for example, using the Network Transport of RTCM via satellite link; through the Internet, for example, using the Network Transport of RTCM via Internet protocol (NTRIP).

### ➤ 2.2. Local Area DGNSS Positioning

Since RS is at known location  $(x_{rs}, y_{rs}, z_{rs})$  we can compute the real distance from RS (Fig. 2) to satellites  $Sat_i$  as

$$D_i^{rs} = \sqrt{(x_i - x_{rs})^2 + (y_i - y_{rs})^2 + (z_i - z_{rs})^2}, i = \overline{1, N}, N \geq 4. \quad (5)$$

We calculate the assessment of the distance from RS (Fig. 2) to satellites  $Sat_i$  (pseudo-range) by determining the signal propagation time from RS to the satellites  $Sat_i$  as

$$\hat{D}_i^{rs} = c \hat{T}_i^{rs}, i = \overline{1, N}, N \geq 4 \quad (6)$$

and now we can compute the correction of a pseudo-range for all vehicles in limited scope:

$$\Delta D_i^{rs} = (\hat{D}_i^{rs} - D_i^{rs}), i = \overline{1, N}, N \geq 4. \quad (7)$$

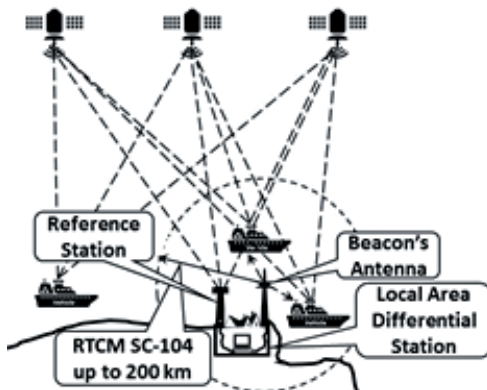


Fig. 4. Local Area Differential GNSS: this figure shows a receiver at a known position (the Reference Station) and a 2nd receiver on board of the vehicle at an unknown position (i. e. the rover or user) for relative positioning. Because the GNSS position errors for the Reference Station and for the rover are approximately the same, the difference between the known and unknown locations of the Reference Station can be used to improve the accuracy of the positioning

The Radio Beacon transmit the correction  $\Delta D_i^{rs}$  to all vehicles, that adjusting their pseudo-range as

$$\tilde{D}_i^\nu = \left( \hat{D}_i^\nu - \Delta D_i^{\tau s} \right) = \left( c \hat{T}_i^\nu - \Delta D_i^{\tau s} \right), i = \overline{1, N}, N \geq 4. \quad (8)$$

In this case the system of the equations (2) assumes the form

$$\sqrt{(x_i - \tilde{x}_v)^2 + (y_i - \tilde{y}_v)^2 + (z_i - \tilde{z}_v)^2} = \tilde{D}_i^v = \left( c\hat{T}_i^v - \Delta D_i^{rs} \right), \quad (9)$$

$$i = \overline{1, N}, N \geq 4.$$

The navigation processor of vehicle solves the system of equations (10) and calculate the position of the vehicle  $(\tilde{x}_v, \tilde{y}_v, \tilde{z}_v)$ . The positioning error may be defined as

$$\Delta D = \sqrt{(x - \tilde{x}_v)^2 + (y - \tilde{y}_v)^2 + (z - \tilde{z}_v)^2} \quad (10)$$

on condition that the real coordinates of the vehicle ( $x, y, z$ ) known since the geodesic accuracy. The support for Differential GNSS positioning technology will solve the positioning problem in high-accuracy (10–20 cm).

### ➤ 2.3. Regional Area DGNSS Positioning

Let's pretend that Regional Area Differential GNSS comprises from  $M$  Reference Station (Fig. 5)

$$RS_j, j = \overline{1, M}. \quad (11)$$

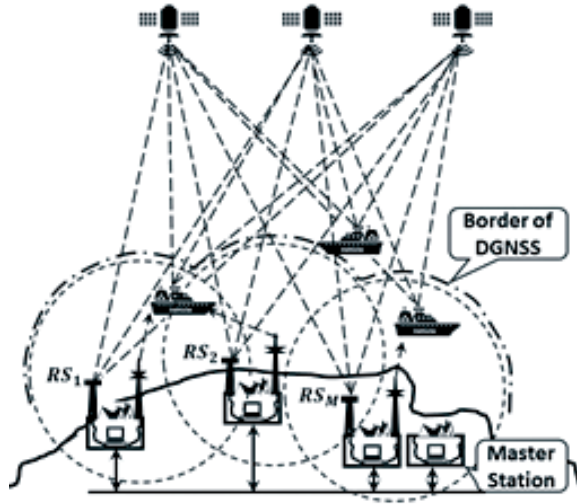


Fig. 5. Regional Area Differential GNSS: this figure shows a receivers at a known position (the Reference Stations) and a receivers on board of the vehicles at an unknown position (i. e. the rover or user) for relative positioning.

The Radio Beacons transmit the local corrections across a radio or wired communication channel to Master Station and Master Station after approximation of local data transmit the regional correction across Radio Beacons or may be through a communication satellite (a selection of communication channel depends on the size and configuration of the region) to all vehicles which are in this region

Since  $RS_j$  are at known locations  $\{x_j^{rs}, y_j^{rs}, z_j^{rs}\}$  we can compute the real distance from  $RS_j$  to satellites  $Sat_i$  as

$$D_{i,j}^{rs} = \sqrt{(x_i - x_j^{rs})^2 + (y_i - y_j^{rs})^2 + (z_i - z_j^{rs})^2}, \quad (12)$$

$$i = \overline{1, N}, N \geq 4, j = \overline{1, M}.$$

We calculate the assessment of the distance from  $RS_j$  to satellites  $Sat_i$  (pseudo-ranges) by determining the signal propagation time from RS to the satellites  $Sat_i$  as

$$\hat{D}_{i,j}^{rs} = c\hat{T}_{i,j}^{rs}, i = \overline{1, N}, N \geq 4, j = \overline{1, M} \quad (13)$$



and now we can compute the correction of a pseudo-ranges for all vehicles in the  $j$ -one limited scopes:

$$\Delta D_{i,j}^{rs} = (\widehat{D}_{i,j}^{rs} - D_{i,j}^{rs}), i = \overline{1, N}, N \geq 4, j = \overline{1, M}. \quad (14)$$

The Radio Beacons transmit the local correction  $\Delta D_{i,j}^{rs}$  to Master Station, which solves the problem of interpolation a plurality of samples  $\Delta D_{i,j}^{rs}$  into distribution functions of positioning. For each navigation satellite we know the value of the function (14) at the interpolation nodes, and we can determine the value of  $\widehat{\Delta D}_i(x, y)$  at any point  $(x, y)$  of a region, in which there are RS. The solution to this problem is to construct a polynomial interpolation of the receiving nodes in the prescribed values and the calculation of the value of this polynomial in a point of interest to us  $(x, y)$  (Table 1).

After approximation of local data Master Station transmit the regional correction  $\widehat{\Delta D}_i(x, y, z)$  across radio beacons or may be through a communication satellite (a selection of communication channel depends on the size and configuration of the region) to all vehicles which are in this region. Each vehicle adjusting their pseudo-ranges as

$$\tilde{D}_i^v = \widehat{D}_i^v - \widehat{\Delta D}_i(x_v, y_v, z_v) = c\widehat{T}_i^v - \widehat{\Delta D}_i(x_v, y_v, z_v), i = \overline{1, N}, N \geq 4. \quad (15)$$

In this case the system of the equations (14) assumes the form

$$\sqrt{(x_i - \tilde{x}_v)^2 + (y_i - \tilde{y}_v)^2 + (z_i - \tilde{z}_v)^2} = \tilde{D}_i^v = c\widehat{T}_i^v - \widehat{\Delta D}_i(x_v, y_v, z_v), \quad (16)$$

$$i = \overline{1, N}, N \geq 4.$$

The navigation processor of vehicle solves the system of equations (16) and calculate the position of the vehicle  $(\tilde{x}_v, \tilde{y}_v, \tilde{z}_v)$ .

It is assumed that  $\widehat{\Delta D}_i(x, y, z)$  tabulated (sampling and quantization), i. e. interpolation results are presented in the form of a four-dimensional array

$$\Delta_{i,k,l,n} = \widehat{\Delta D}_i(x_{\min} + k \cdot \Delta x, y_{\min} + l \cdot \Delta y, z_{\min} + n \cdot \Delta z), i = \overline{1, N}, \quad (17)$$

$$\text{where } k = 0, \frac{x_{\max} - x_{\min}}{\Delta x} - 1, l = 0, \frac{y_{\max} - y_{\min}}{\Delta y} - 1, n = 0, \frac{z_{\max} - z_{\min}}{\Delta z} - 1,$$

$(\Delta x, \Delta y, \Delta z)$  — steps sampling of function  $\widehat{\Delta D}_i(x, y, z)$ .

Table 1

3D (XYZ) interpolation irregular grid (U is the symbol of interpolation)

$RS_{j,j} = \overline{1, M}$				Interpolation for the region $\{x_{\min} \leq x \leq x_{\max}, y_{\min} \leq y \leq y_{\max}, z_{\min} \leq z \leq z_{\max}\}$
1	2	...	M	
1 $\Delta D_{1,1}^{\pi}(x_1^{\pi}, y_1^{\pi}, z_1^{\pi})$	$\Delta D_{1,2}^{\pi}(x_2^{\pi}, y_2^{\pi}, z_2^{\pi})$	...	$\Delta D_{1,M}^{\pi}(x_M^{\pi}, y_M^{\pi}, z_M^{\pi})$	$\widetilde{\Delta D}_1(x, y, z) = \bigcup_{j=1}^M \{\Delta D_{1,j}^{\pi}(x_j^{\pi}, y_j^{\pi}, z_j^{\pi})\}$
2 $\Delta D_{2,1}^{\pi}(x_1^{\pi}, y_1^{\pi}, z_1^{\pi})$	$\Delta D_{2,2}^{\pi}(x_2^{\pi}, y_2^{\pi}, z_2^{\pi})$	...	$\Delta D_{2,M}^{\pi}(x_M^{\pi}, y_M^{\pi}, z_M^{\pi})$	$\widetilde{\Delta D}_2(x, y, z) = \bigcup_{j=1}^M \{\Delta D_{2,j}^{\pi}(x_j^{\pi}, y_j^{\pi}, z_j^{\pi})\}$
...	...	...	...	...
N $\Delta D_{N,1}^{\pi}(x_1^{\pi}, y_1^{\pi}, z_1^{\pi})$	$\Delta D_{N,2}^{\pi}(x_2^{\pi}, y_2^{\pi}, z_2^{\pi})$	...	$\Delta D_{N,M}^{\pi}(x_M^{\pi}, y_M^{\pi}, z_M^{\pi})$	$\widetilde{\Delta D}_N(x, y, z) = \bigcup_{j=1}^M \{\Delta D_{N,j}^{\pi}(x_j^{\pi}, y_j^{\pi}, z_j^{\pi})\}$

$Sat_i, i = \overline{1, N}, N \geq 4$

Table 2

2D (XY) interpolation irregular grid (U is the symbol of interpolation)

$RS_{j,j} = \overline{1, M}$				Interpolation for the region $\{x_{\min} \leq x \leq x_{\max}, y_{\min} \leq y \leq y_{\max}\}$
1	2	...	M	
1 $\Delta D_{1,1}^{\pi}(x_1^{\pi}, y_1^{\pi})$	$\Delta D_{1,2}^{\pi}(x_2^{\pi}, y_2^{\pi})$	...	$\Delta D_{1,M}^{\pi}(x_M^{\pi}, y_M^{\pi})$	$\widetilde{\Delta D}_1(x, y) = \bigcup_{j=1}^M \{\Delta D_{1,j}^{\pi}(x_j^{\pi}, y_j^{\pi})\}$
2 $\Delta D_{2,1}^{\pi}(x_1^{\pi}, y_1^{\pi})$	$\Delta D_{2,2}^{\pi}(x_2^{\pi}, y_2^{\pi})$	...	$\Delta D_{2,M}^{\pi}(x_M^{\pi}, y_M^{\pi})$	$\widetilde{\Delta D}_2(x, y) = \bigcup_{j=1}^M \{\Delta D_{2,j}^{\pi}(x_j^{\pi}, y_j^{\pi})\}$
...	...	...	...	...
N $\Delta D_{N,1}^{\pi}(x_1^{\pi}, y_1^{\pi})$	$\Delta D_{N,2}^{\pi}(x_2^{\pi}, y_2^{\pi})$	...	$\Delta D_{N,M}^{\pi}(x_M^{\pi}, y_M^{\pi})$	$\widetilde{\Delta D}_N(x, y) = \bigcup_{j=1}^M \{\Delta D_{N,j}^{\pi}(x_j^{\pi}, y_j^{\pi})\}$

$Sat_i, i = \overline{1, N}, N \geq 3$

For example, there are base stations in the territory of the Polish Republic in the ASG-EUPOS system (Fig. 6).



Fig. 6. Distribution of ASG-EUPOS reference stations  
(with kind permission from Bujakowski-Surveyor General of Poland)<sup>6</sup>

In Fig. 7 you can see the coverage area of the territory of the Polish Republic by the correction field.

## ➤ 2.4. Maritime Wide Area DGNSS Positioning

A network of reference stations is the base unit which provides high precision coordinate-time information about the location of vessels in coastal waters<sup>7</sup>. This network is organized in areas where the density of traffic and the existing navigation and hydrographic support of navigation safety are demanding higher levels of courts in order to protect the environment and re-

<sup>6</sup> Head Office of Geodesy and Cartography. Poland, 2013 [Electronic Resource]. URL: [http://www.asgeupos.pl/webpg/graph/dwnld/map\\_en\\_dwnld.jpg](http://www.asgeupos.pl/webpg/graph/dwnld/map_en_dwnld.jpg) [URL Address is available 5/14/2017 6:48 PM].

<sup>7</sup> This section deals with the problems of maritime transport, but the results of this section can be extended to all types of vehicles.

duce downtime of vessels and to achieve smooth operation of the fleet, providing quality rescue at sea.

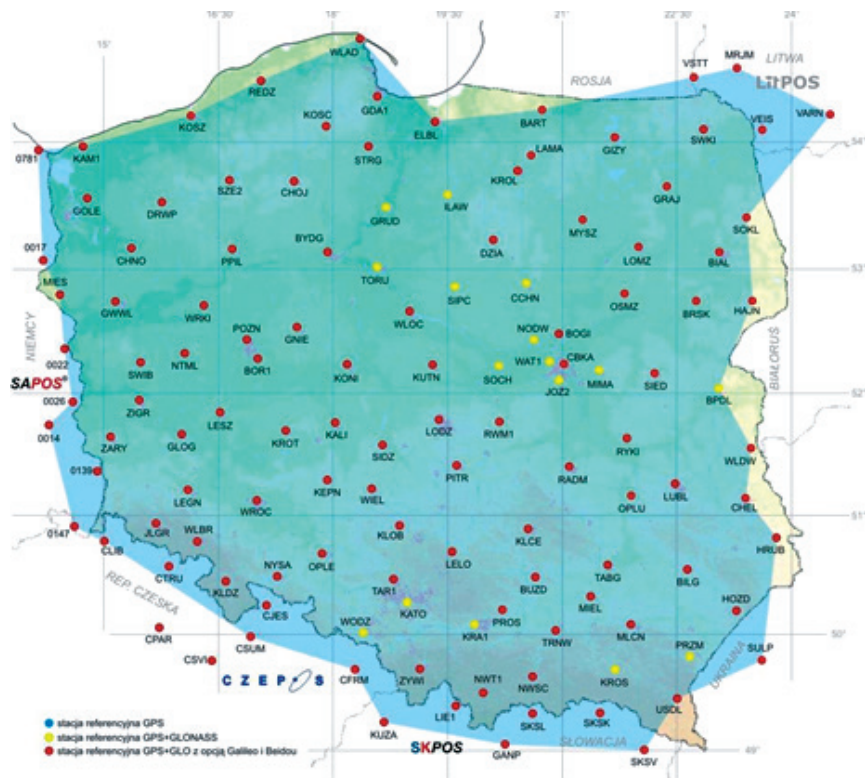


Fig. 7. ASG-EUPOS system description. NetRTK GPS+GLO coverage area<sup>8</sup>

The Radio Beacons transmit the local correction  $\Delta D_{i,j}^{rs}$  to Master Station, which solves the problem of interpolation a plurality of samples  $\Delta D_{i,j}^{rs}$  into distribution functions of positioning. For each navigation satellite we know the value of the function (15) at the interpolation nodes, and we can determine the value of  $\widehat{\Delta D}_i(x, y)$  at any point  $(x, y)$  of a region, in which there are RS. The solution to this problem is to construct a polynomial interpolation of the receiving nodes in the prescribed values and the calculation of the value of this polynomial in a point of interest to us  $(x, y)$  (Table 2).

<sup>8</sup> ASG-EUPOS [Electronic Resource]. URL: [http://www.asgeupos.pl/webpg/graph/img/\\_syst\\_descr/stations\\_gg\\_EN.png](http://www.asgeupos.pl/webpg/graph/img/_syst_descr/stations_gg_EN.png) [URL Address is available 5/14/2017 6:48 PM].

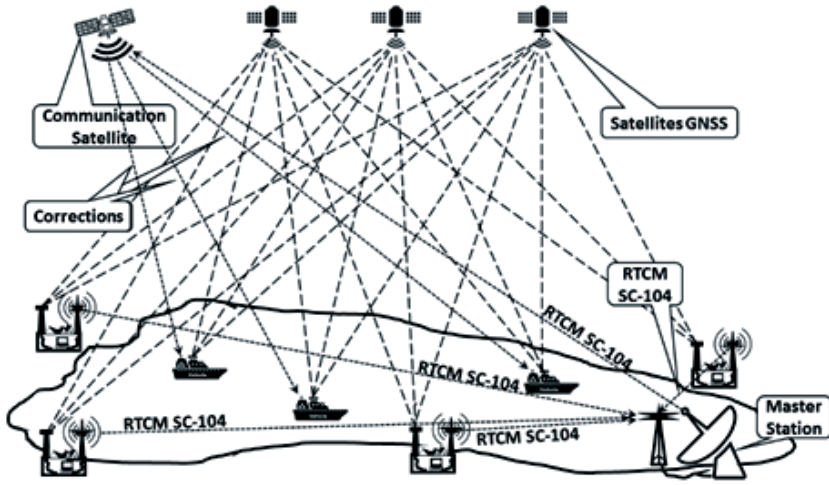


Fig. 8. Wide Area Differential GNSS: this figure shows a receivers at a known position (the Reference Stations) and a receivers on board of the vehicles at an unknown position (i. e. the rover or user) for relative positioning. The Radio Beacons transmit the local corrections across a radio or wired communication channel to Master Station and Master Station after approximation of local data transmit the wide correction across a communication satellite or group of satellites to all vehicles

And the expression (17) takes the form

$$\Delta_{i,k,l} = \widehat{\Delta D}_i(x_{\min} + k \cdot \Delta x, y_{\min} + l \cdot \Delta y), i = \overline{1, N}, N \geq 3, \quad (18)$$

where  $k = 0, \frac{x_{\max} - x_{\min}}{\Delta x} - 1, l = 0, \frac{y_{\max} - y_{\min}}{\Delta y} - 1$ ,  $\Delta x, \Delta y$  — steps sam-

pling of function  $\widehat{\Delta D}_i(x, y)$ .

In practice, the task of 2D interpolation on a non-uniform grid can be solved using standard software procedures, such as MATLAB — a two-dimensional interpolation on the irregular grid:

*Syntax:  $ZI = \text{griddata}(x, y, z, XI, YI)$  Description: Function  $ZI = \text{griddata}(x, y, z, XI, YI)$  returns an array of  $ZI$ , which is defined on the new grid  $\{XI, YI\}$  as a result of interpolation of the initial function  $z$ , defined on a non-uniform grid  $\{x, y\}$  i. e.  $z = f(x, y)$ .*

Two examples of the task solutions of 2D interpolation on a non-uniform grid for 13 RS<sup>9</sup> (a) and for 8 RS<sup>10</sup> (b), located in  $\{14 \leq E \leq 15; 54 \leq N \leq 55\}$  (Fig. 9). As  $Z$  used the sum of two fields (random and deterministic)

$$Z(E, N) = \left( \frac{REND()}{10} - 1, 2 \right) + \frac{1}{2\pi\sigma_E\sigma_N} e^{-\frac{(E-14,5)^2}{2\sigma_E^2} - \frac{(N-54,5)^2}{2\sigma_N^2}} \quad (19)$$

where  $0 \leq REND() \leq 1$  is a random number,  $\sigma_E = \sigma_N = 0,5$ .

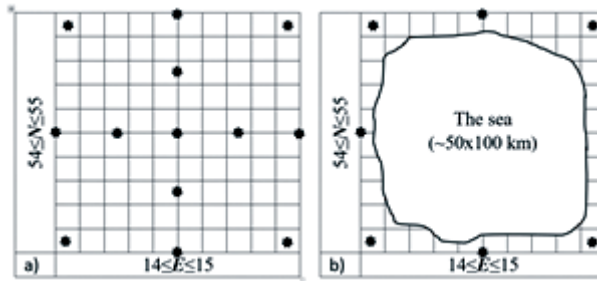


Fig. 9. A two non-uniform grids: a) 13 RS on the ground ( $\sim 60 \times 110$  km); b) 8 RS by the sea ( $\sim 50 \times 100$  km)

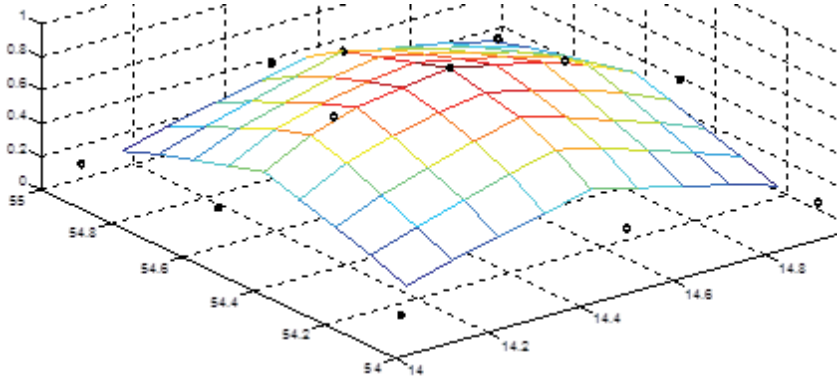


Fig. 10. 2D interpolation on a non-uniform grid for 13 RS as fig. 9, a)

<sup>9</sup>  $E = [14.00 \ 14.05 \ 14.05 \ 14.25 \ 14.50 \ 14.50 \ 14.50 \ 14.50 \ 14.50 \ 14.75 \ 14.95 \ 14.95 \ 15.00];$   
 $N = [54.50 \ 54.05 \ 54.95 \ 54.50 \ 54.00 \ 54.25 \ 54.50 \ 54.80 \ 55.00 \ 54.50 \ 54.05 \ 54.95 \ 54.50];$   
 $Z = [0.400 \ 0.170 \ 0.170 \ 0.750 \ 0.390 \ 0.730 \ 0.850 \ 0.650 \ 0.370 \ 0.700 \ 0.150 \ 0.220 \ 0.39];$   
 $e = 14:0.1:15; n = 54:0.1:55; [XI, YI] = \text{meshgrid}(e, n);$   
 $ZI = \text{griddata}(E, N, Z, XI, YI); \text{mesh}(XI, YI, ZI), \text{hold on}, \text{plot3}(E, N, Z, 'ok')$

<sup>10</sup>  $E = [14.00 \ 14.05 \ 14.05 \ 14.50 \ 14.50 \ 14.95 \ 14.95 \ 15.00];$   
 $N = [54.50 \ 54.05 \ 54.95 \ 54.00 \ 55.00 \ 54.05 \ 54.95 \ 54.50];$   
 $Z = [0.400 \ 0.170 \ 0.170 \ 0.390 \ 0.370 \ 0.150 \ 0.220 \ 0.39];$   
 $e = 14:0.1:15; n = 54:0.1:55; [XI, YI] = \text{meshgrid}(e, n);$   
 $ZI = \text{griddata}(E, N, Z, XI, YI); \text{mesh}(XI, YI, ZI), \text{hold on}, \text{plot3}(E, N, Z, 'ok')$

The application griddata is admissible only for 2D vehicle (ship, vessel, boat, car, etc.), i. e. for the case where  $z_j^{rs} = \text{const}$ . For each navigation satellite  $i = \overline{1, N}, N \geq 3$  we replace 3D non-uniform grid  $\Delta D_{i,j}^{rs}(x_j^{rs}, y_j^{rs}, z_j^{rs})$  (Table 2) on 2D non-uniform grid  $\Delta D_{i,j}^{rs}(x_j^{rs}, y_j^{rs}), j = \overline{1, M}$ . Determine uniform grid  $\{XI, YI\}$  in the region  $\{x_{\min} \leq x \leq x_{\max}, y_{\min} \leq y \leq y_{\max}\}$  with sampling steps  $\{\Delta x, \Delta y\}$  and we use procedure griddata as and we use procedure griddata (Fig. 11).

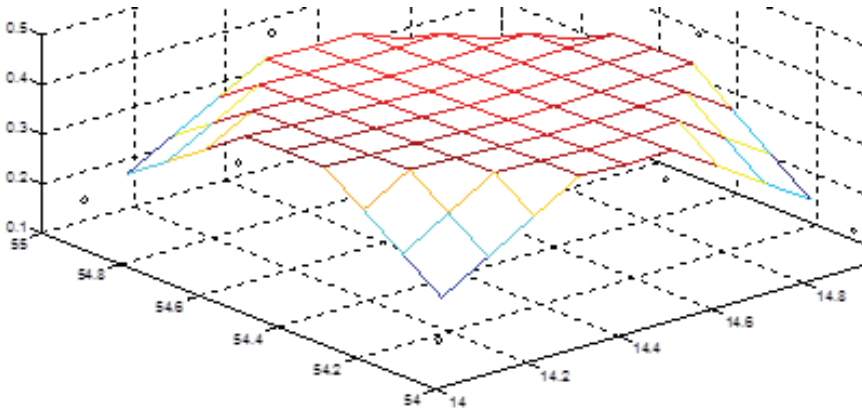


Fig. 11. 2D interpolation on a non-uniform grid for 8 RS as fig. 9, b)

For  $i = \overline{1, N} \% N \geq 3$  because it considered only 2D vehicle (ship, vessel, boat, car, etc.)

$ZI = \text{griddata}(x_*^{rs}, y_{*1}^{rs}, \Delta D_{i,*}^{rs}, XI, YI) \% \text{ Symbol } (*) \text{ means all elements of the array}$

$\Delta_{i,*,*} = ZI$

End

## 2.5. Moving DGNSS Positioning

One drawback of Differential GNSS is that the installation of Differential Station requires a significant investment in the geodetic reference. In the case of rapid deployment of Differential GNSS can be used Moving Differential GNSS (Fig. 12).

Basic data GNSS ( $N$  height and width of the space  $E$ ) are clustered around a central point (Fig. 13).



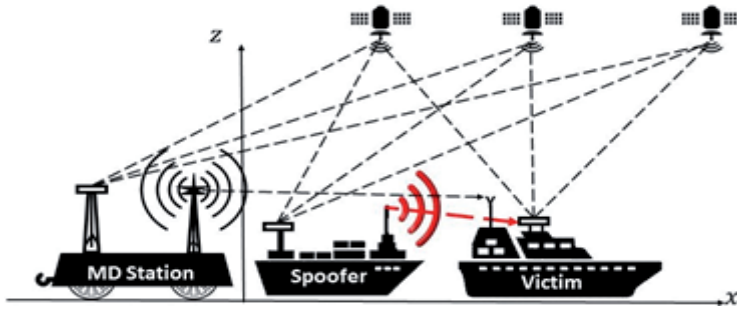


Fig. 12. Detection of GNSS spoofing in MDGNSS mode: shore-based Moving Differential Station (MDS)

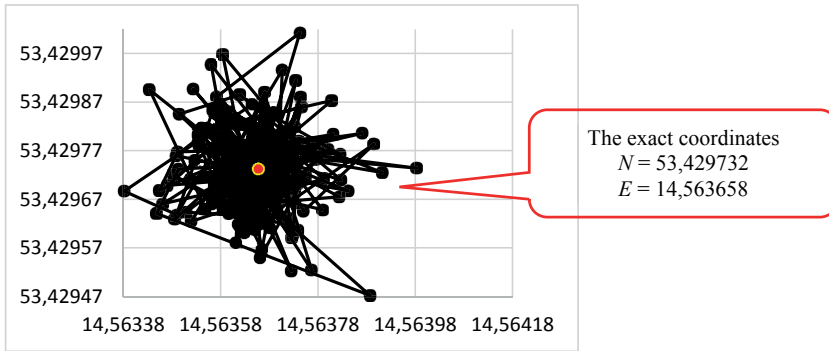


Fig. 13. Example of focusing N and E around a central point

Assume that moving BS is set at a point with unknown coordinates  $(E, N)$ . Moving BS receives signals from navigation satellites and determine its current position with a periodicity  $\Delta t$ .

$$(E_i, N_i), i = \overline{1, \infty}. \quad (20)$$

Thus, in order to determine their coordinates  $(E, N)$  with sufficient accuracy to calculate the value of the arithmetic average  $(\tilde{E}_I, \tilde{N}_I)$  of  $(E_i, N_i)$  at time  $I\Delta t$

$$\tilde{E}_I = \frac{1}{I} \sum_{i=1}^I E_i, \tilde{N}_I = \frac{1}{I} \sum_{i=1}^I N_i. \quad (21)$$

So, for example, we have 200 samples of  $N_i$  (Fig. 14) and the estimates for the coordinates  $N$  for  $I = \overline{1, 200}$  (Fig. 15).

$$\tilde{N}_I = \frac{1}{I} \sum_{i=1}^I N_i \quad (22)$$



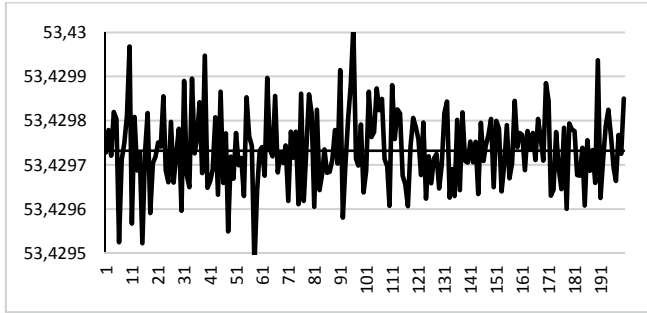


Fig. 14. An example of the measurements  $N_i, i = \overline{1, 200}$ ,  $\Delta t = 1s$

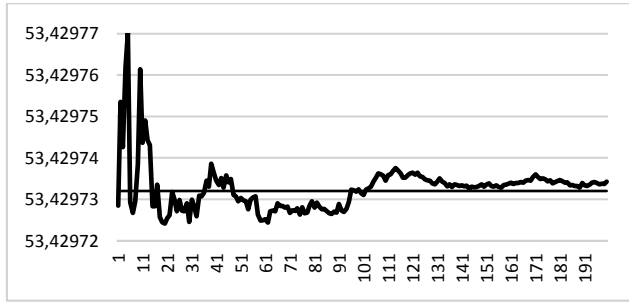


Fig. 15. An example of the computing  $\tilde{N}_I, I = \overline{1, 200}$ ,  $\Delta t = 1s$

In this example for measurements  $E$  we have 200 samples of  $E_i$  (Fig. 16) and the estimates for the coordinates  $E$  for  $I = \overline{1, 200}$  (Fig. 17).

$$\tilde{E}_I = \frac{1}{I} \sum_{i=1}^I E_i. \quad (23).$$

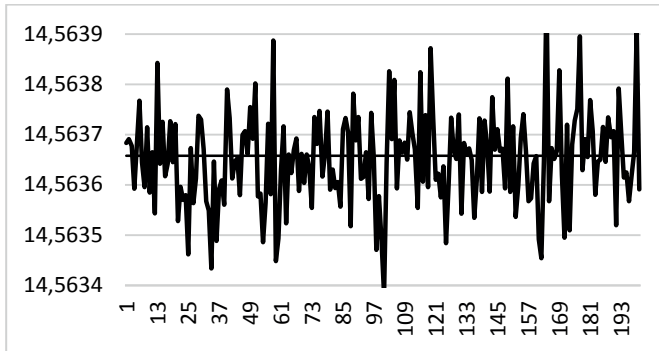


Fig. 16. An example of the measurements  $E_i, i = \overline{1, 200}$ ,  $\Delta t = 1s$



Fig. 17. An example of the computing  $\tilde{E}_I, I = \overline{1, 200}, \Delta t = 1s$

The arithmetic means of geographic coordinates of moving BS ( $\tilde{N}_I$  and  $\tilde{E}_I$ ) are clustered around a central point (Fig. 18).

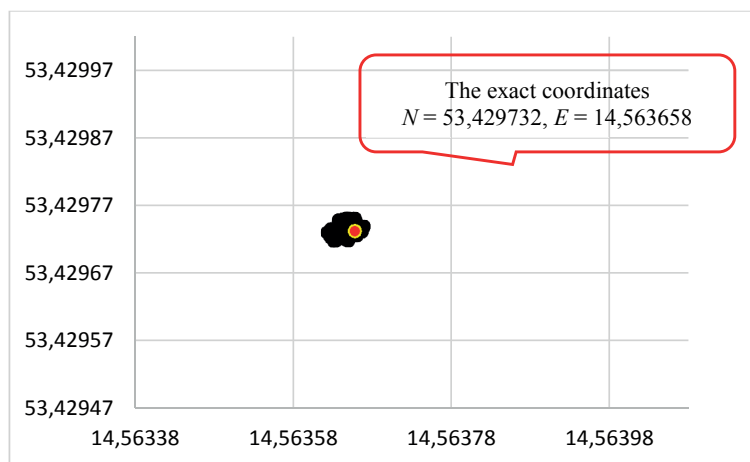


Fig. 18. Example of focusing  $\tilde{N}_I$  and  $\tilde{E}_I$  around a central point

Comparing figures 13 and 18 we can conclude that with the technology of the moving BS we can be arranged Moving DGNSS with an acceptable accuracy for many applications. Selecting  $I$  depends on the requirements of positioning accuracy BS, which increases with increasing  $I$ .

### 3. GNSS and DGNSS Spoofing

#### ➤ 3.1. GNSS Spoofing

The spoofer can be built on the basis of laboratory GNSS signal generator designed for debugging GNSS receivers. Spoofing is possible to build a system based on a particular set of SDR (Software-defined radio — soft-

ware-defined radio), for they have the appropriate software. Approximate cost is 1–10 thousand euro. A victim moves in space with the civil GNSS procedure and is subjected to an spoofing attack from other vehicles on the ground or at sea, which will called “spoofers”. GNSS spoofing is the GNSS signal conversion technology. Spoofers plans to organize an attack, so that the navigator should not know that the signal received by GNSS receiver is false. As a result of an organized attack, the navigator determines wrong time and/or location. This means that the spoofers began to administer the GNSS position in time and space.

The distortion of the signal includes a signal capture and playback at the same frequency with a slight shift in time and with greater intensity, in order to deceive the electronic equipment of a victim and, respectively, co-driver, of course, if there is one on board the vehicle.

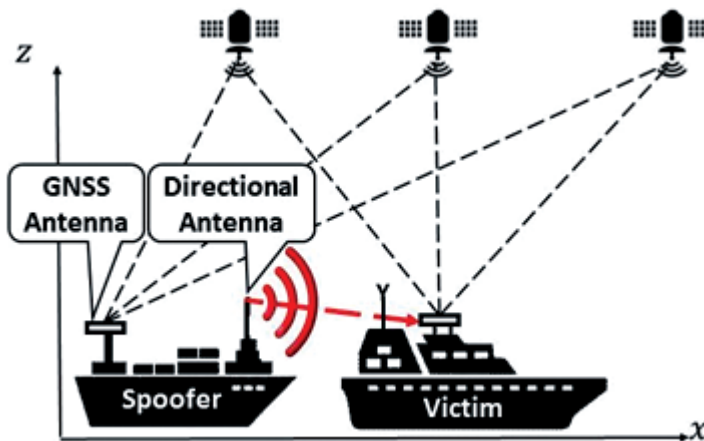


Fig. 19. GNSS Spoofing: a vehicles, such as unmanned aircraft or helicopter, the vessel etc., called a victim

The only GNSS system which can't be deceived, are GNSS military systems, that utilizes principles of cryptography. However, for GNSS civil use such protection doesn't exist. Therefore, the research of spoofing property for anti-spoofers design must be conducted. The spoofing main idea is illustrated in Fig. 9. Spoofers are generally located in the immediate vicinity of the victim and moves in space with civilian or military GNSS mode (L1 or L1/L2).

Spoofers perform short-term disruption of the GNSS signal L1 using GNSS jammer. As a result of jamming GNSS receiver „loses satellites” and starts looking for GNSS signals. At this time, spoofers include imitator GNSS signals, which is set up to imitate the new coordinates of the GNSS receiver. Generally, GNSS signal strength exceeds the strength of imitator real GNSS signals and GNSS receiver can't determine from what time of its movement in space it is controlled by a spoofers.

### ➤ 3.2. DGNSS Spoofing

The Radio Beacon of spoofer transmit the false correction  $\Delta D_i^f$  to the victim, that “adjusting” their pseudo-range as

$$\tilde{D}_i^v = \left( \hat{D}_i^v - \Delta D_i^f \right) = \left( c\hat{T}_i^v - \Delta D_i^f \right), i = \overline{1, N}, N \geq 4. \quad (24)$$

In this case the system of the equations (2) assumes the form

$$\left\{ \sqrt{(x_i - \tilde{x}_f)^2 + (y_i - \tilde{y}_f)^2 + (z_i - \tilde{z}_f)^2} = \left( c\hat{T}_i^v - \Delta D_i^f \right) \right\} \rightarrow (\tilde{x}_f, \tilde{y}_f, \tilde{z}_f), \quad (25)$$

$$i = \overline{1, N}, N \geq 4.$$

The navigation processor of vehicle solves the system of equations (22) and calculate the false position of the victim  $(\tilde{x}_f, \tilde{y}_f, \tilde{z}_f)$ .

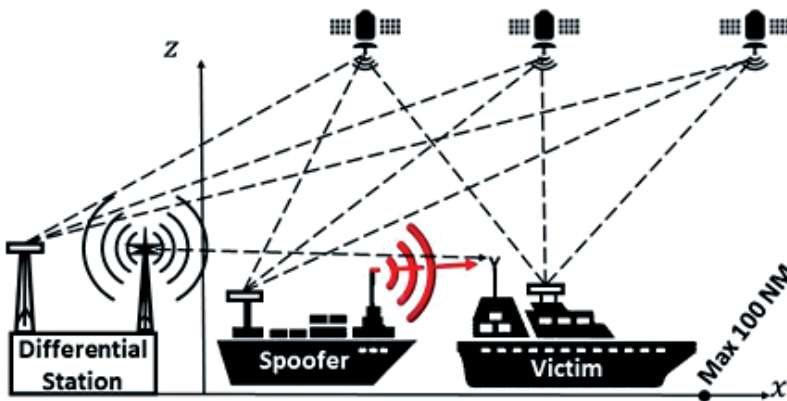


Fig. 20. DGNSS Spoofing

## 4. GNSS and DGNSS Spoofing Detection

### ➤ 4.1. Spoofing Detection of Local Area DGNSS Positioning

The navigation processor of victim solves the system of the equations (26) [8–12]

$$\sqrt{(x_i - x_v)^2 + (y_i - y_v)^2 + (z_i - z_v)^2} = c\hat{T}_i^v, i = \overline{1, N}, N \geq 4 \quad (26)$$

and calculates the coordinates of the victim  $(x_v, y_v, z_v)$  using the GNSS signals without any corrections. It then computes the distance between the two victim positions

$$\widetilde{\Delta D} = \sqrt{(x_v - \tilde{x}_f)^2 + (y_v - \tilde{y}_f)^2 + (z_v - \tilde{z}_f)^2}. \quad (27)$$

If the vehicle is not exposed to the type of spoofing attack, the difference between the calculated coordinates cannot exceed a certain maximum positioning error  $\Delta D_{\max}$  on normal mode GNSS (DGNSS mode is not available), i. e.

$$\widetilde{\Delta D} \leq \Delta D_{\max} \quad (28)$$

and the decision rule of algorithm for spoofing's determining can be written as

$$\text{if } (\widetilde{\Delta D} \leq \Delta D_{\max}) \text{ then OK else goto SPOOFING.} \quad (29)$$

#### ➤ 4.2. Spoofing Detection of Maritime Wide Area DGNSS

The Radio Beacons transmit the local corrections across a radio or wired communication channel to Master Station and Master Station after approximation of local data transmit the wide correction across a telecommunication satellite to all vehicles that adjusting their pseudo-range<sup>11</sup>.

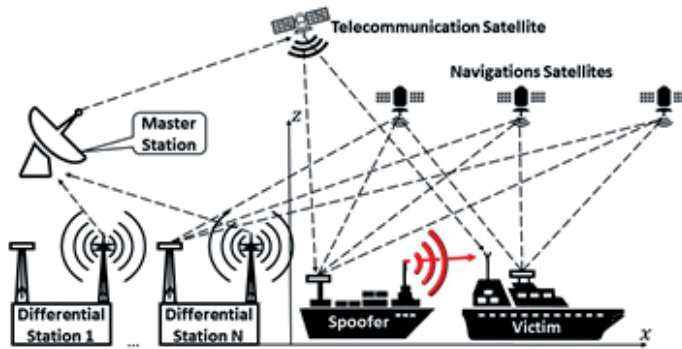


Fig. 21. Spoofing Detection of Maritime Wide Area Differential GNSS

The Radio Beacon of spoofer transmit the false correction  $\Delta D_i^f$  to the victim, that “adjusting” their pseudo-range as

$$\tilde{D}_i^v = (\hat{D}_i^v - \Delta D_i^f) = (c\hat{T}_i^v - \Delta D_i^f), i = \overline{1, N}, N \geq 3. \quad (30)$$

In this case we can make the system of the equations

$$\sqrt{(x_i - \tilde{x}_f)^2 + (y_i - \tilde{y}_f)^2 + z_i^2} = (c\hat{T}_i^v - \Delta D_i^f), i = \overline{1, N}, N \geq 3. \quad (31)$$

<sup>11</sup> The section “Spoofing Detection using Regional Area Differential GNSS” omitted because implemented similarly. We consider 2D Spoofing Detection for maritime applications.

The navigation processor of victim solves the system of equations (31) and calculate the false position of the victim  $(\tilde{x}_f, \tilde{y}_f)$ , solves the system of equations (32) and calculate the coordinates of the victim  $(x_v, y_v)$  for  $N \geq 3$  using the GNSS signals without any corrections.

$$\left\{ \sqrt{(x_i - x_v)^2 + (y_i - y_v)^2 + z_i^2} = c\hat{T}_i^v \right\} \rightarrow (x_v, y_v). \quad (32)$$

It then computes the distance between the two vehicle positions

$$\widetilde{\Delta D} = \sqrt{(x_v - \tilde{x}_f)^2 + (y_v - \tilde{y}_f)^2}. \quad (33)$$

If the vehicle is not exposed to the type of spoofing attack, the difference between the calculated coordinates cannot exceed a certain maximum positioning error  $\Delta D_{\max}$  on normal mode GNSS (DGNSS mode is not available), i. e.

$$\widetilde{\Delta D} \leq \Delta D_{\max} \quad (34)$$

and the decision rule of algorithm for spoofing's determining can be written as

$$\text{if } (\widetilde{\Delta D} \leq \Delta D_{\max}) \text{ then OK else goto SPOOFING.} \quad (35)$$

#### ➤ 4.3. Spoofing Detection of Shore-based Moving DGNSS

Since BS is at location  $(\tilde{N}_I, \tilde{E}_I)$  we can compute the real distance from BS to satellites  $\text{Sat}_i$  as

$$D_i^{rs} = \sqrt{(x_i - \tilde{E}_I)^2 + (y_i - \tilde{N}_I)^2 + z_i^2}, i = \overline{1, N}, N \geq 3. \quad (36)$$

We calculate  $\hat{\rho}_i^{bs}$ ,  $\Delta \rho_i^{bs}$ ,  $\tilde{\rho}_i^v$ ,  $(\tilde{x}_v, \tilde{y}_v)$  and  $(x_v, y_v)$  by analogy with sections "Differential GNSS Positioning" and "Spoofing Detection using Differential GNSS" and then we can compute the distance between the two vehicle positions  $(\tilde{x}_v, \tilde{y}_v)$  and  $(x_v, y_v)$  as

$$\widetilde{\Delta D} = \sqrt{(x_v - \tilde{x}_v)^2 + (y_v - \tilde{y}_v)^2}. \quad (37)$$

If the vehicle is not exposed to the type of spoofing attack, the difference between the calculated coordinates cannot exceed a certain maximum positioning error  $\Delta D_{\max}$  on normal mode GNSS (DGNSS mode is not available), i. e.

$$\widetilde{\Delta D} \leq \Delta D_{\max} \quad (38)$$

and the decision rule of algorithm for spoofing's determining can be written as

$$\text{if } (\widetilde{\Delta D} \leq \Delta D_{\max}) \text{ then OK else goto SPOOFING.} \quad (39)$$

#### ➤ 4.4. Spoofing Detection of Offshore Moving DGNSS

If you want to use Differential GNSS offshore ( $> 200$  km), the MDS = RS + RB can be placed on a floating platform with the anchor, such as shown in Fig. 22. Under the influence of the wind and water currents MDS constantly drifting, so can be used to estimate the coordinates of MDS  $(E, N)$  with sufficient accuracy to calculate the value of the arithmetic average  $(\tilde{E}_I, \tilde{N}_I)$  of  $(E_i, N_i)$  at time  $I\Delta t$

$$\tilde{E}_j = \frac{1}{I} \sum_{i=1}^I E_{i+j}, \tilde{N}_j = \frac{1}{I} \sum_{i=1}^I N_{i+j}, I = [T_w / \Delta t], j = \overline{I, \infty}, \quad (40)$$

$T_w$  – window of the average.

This means that with a frequency  $1/\Delta t$  there is a sliding updated estimates  $(E, N)$  in a time window  $T_w$ .

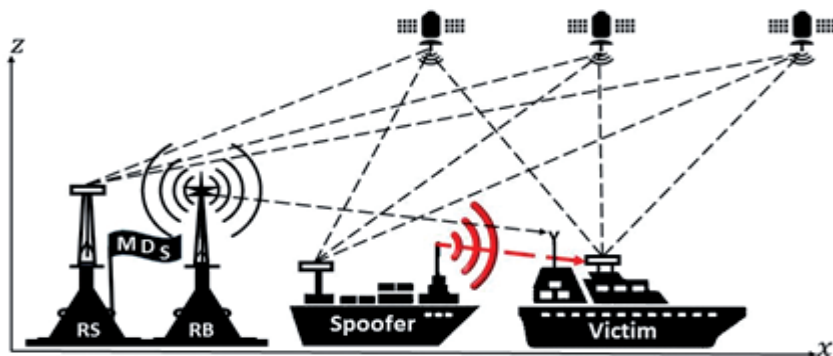


Fig. 22. Detection of GNSS spoofing in Offshore Moving DGNSS mode

Selecting  $T_w$  depends on the requirements of positioning accuracy BS, which increases with increasing  $T_w$ . It is important that during  $T_w$  MDS coordinates would not change more than a predetermined positioning accuracy. Detailed analysis and resolution of this conflict is beyond the scope of this article.

Since BS is at location  $(\tilde{N}_j, \tilde{E}_j)$  we can compute the real distance from BS to satellites  $\text{Sat}_i$  as

$$\rho_{i,j}^{rs} = \sqrt{(x_i - \tilde{E}_j)^2 + (y_i - \tilde{N}_j)^2 + z_i^2}, i = \overline{1, N}, N \geq 3, j = \overline{I, \infty}. \quad (41)$$

We calculate  $\hat{\rho}_{i,j}^{bs}$ ,  $\Delta \rho_{i,j}^{bs}$ ,  $\tilde{\rho}_{i,j}^v$ ,  $(\tilde{x}_{v,j}, \tilde{y}_{v,j})$  and  $(x_{v,j}, y_{v,j})$  by analogy with sections “Differential GNSS Positioning” and “Spoofing Detection using Differential GNSS” and then we can compute the distance between the two vehicle positions  $(\tilde{x}_{v,j}, \tilde{y}_{v,j})$  and  $(x_{v,j}, y_{v,j})$  as

$$\widetilde{\Delta D}_j = \sqrt{(x_{v,j} - \tilde{x}_{v,j})^2 + (y_{v,j} - \tilde{y}_{v,j})^2}, j = \overline{1, \infty}. \quad (42)$$

If the vehicle is not exposed to the type of spoofing attack, the difference between the calculated coordinates cannot exceed a certain maximum positioning error  $\Delta D_{\max}$  on normal mode GNSS (DGNSS mode is not available), i. e.

$$\widetilde{\Delta D}_j \leq \Delta D_{\max}, j = \overline{1, \infty} \quad (43)$$

and the decision rule of algorithm for spoofing's determining can be written as

$$\text{if } \widetilde{\Delta D}_j \leq \Delta D_{\max} \text{ then OK else goto SPOOFING, } j = \overline{1, \infty}. \quad (44)$$

## 5. Summary and conclusions

The risk of losing GNSS signal is growing every day. The accessories for the manufacture of systems GNSS “Jamming and/or Spoofing” are now widely available and it can take advantage of not only military, but also terrorists. The distortion of the signal includes a signal capture and playback at the same frequency with a slight shift in time and with greater intensity, in order to deceive the electronic equipment of a victim and, respectively, co-driver, of course, if there is one on board the vehicle. The price of one chip-set of such equipment is in the range of 1–10 thousand euros, depending on the dimensions and weight parameters. The principles of spoofing detection of local, regional and wide DGNSS, in which a correction signals of differential station uses for spoofing and for detection of spoofing are constantly evolving. But this methods has one obvious drawback — is supposed to use a fixed (stationary) differential GNSS station. Our many years of research in the field of spoofing detection [8–12] give us confidence that this deficiency is avoidable thanks implement mobile differential station, including floating.

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### Information about the author

**Evgeny Ochinn** (E. Ochinn (at) AM. Szczecin.pl) (phone mobile +48 608 437 562) is a Professor at Maritime University (<http://am.szczecin.pl>), Szczecin, Institute of Marine Computer Science, Faculty of Navigation (ul. Wały Chrobrego 1–2, 70–500 Szczecin, Republic Poland).